Dense Outflows and Deep Convection in the Antarctic Zone of the Southern Ocean

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LONG-TERM GOALS

This project seeks to quantify and better define the dynamics of those processes, including mixing, tides, current-topography interactions and nonlinear equation of state phenomena, that impact vertical transports of heat and mass in the Southern Ocean. These transports are crucial to the formation of Antarctic Bottom Water (AABW) and are integral to the Southern Ocean branch of the meridional overturning circulation (MOC). Improved understanding of the related processes will enhance our ability to predict climate-related changes in the MOC.

OBJECTIVES

Specific objectives are to:

- Quantify and dynamically assess the impacts of tidal currents, steep and irregular bottom topography, and nonlinearities in the seawater equation of state on pathways, transport and mixing of dense outflows in the Southern Ocean, with emphasis on the Ross Sea contribution to AABW..
- Assess seasonal impacts, with an emphasis on regional shelf-slope currents, on Ross Sea dense outflows.
- Assess turbulent mixing responses at small and microscales to externally imposed conditions of varying vertical shear and stability, with an emphasis on the role of the seawater equation of state and with potential relevance to deep ocean convection.

APPROACH

This project relies on analyses of field data that were acquired from the Southern Ocean, primarily from the Ross Sea region, from 2003 to 2005 under the auspices of the international AnSlope (Antarctic Slope) Project. These data include seawater temperature, salinity and current data, and scalar and shear microstructure. Analyses rely on established methods including classical water mass, spectral, and tidal analyses. Findings from the field data analyses are compared with results from laboratory, analytical and numerical modeling work. Results are compared and contrasted, when possible, with those from other regions having similar physical characteristics. The work has been done in collaboration with the AnSlope Project.

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14. ABSTRACT
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WORK COMPLETED

Funding for this grant was received approximately halfway through this fiscal year. Work completed follows from ongoing tasks that were initiated under previous ONR Grant N00014-03-1-0067.

Three manuscripts have been completed, submitted, accepted and are now in press [*Gordon et al.*, 2009; *Padman et al.*, 2009; *Muench et al.*, 2009a]. These manuscripts describe and discuss the physical characteristics and dynamics of the dense outflow from the NW Ross Sea and assess the impact of strong regional tidal currents on the outflow. A fourth manuscript, just submitted, presents preliminary results on the interactions between dense outflows and corrugated seafloor topography, with emphasis on the Ross Sea case [*Muench et al.*, 2009b]. An abstract assessing tidal impacts on upper ocean and sea ice conditions in the marginal seas surrounding Antarctica has been submitted for presentation at the Fall 2008 AGU meeting.

RESULTS

Overview

This project has focused on completing an assessment of a dense outflow exiting the NW Ross Sea shelf, from where it flows downslope and contributes to the AABW. Drygalski Trough, the westermost of several troughs cutting the NW Ross Sea shelf, was the primary source for the outflow. Water from this source is the most saline of those originating from the Ross Sea, having its primary origin in brine rejection along the coast and ice front farther south. The outflow, observed in the summers of 2003 and 2004, exited the shelf over the shelf break sill at the northern end of Drygalski Trough (Fig. 1). Flow thickness, ~100 m near the 600 m deep shelf break, increased to ~400 m on the upper slope near 1200 m depths. The mean pathway trended ~35° downslope from isobaths over the steep upper slope. Outflow speeds routinely approached 0.5 m s^{-1}, leading to a net seaward AABW transport of ~1.7 Sv (1 Sv = 10^{-6} m^3 s^{-1}) on the lower slope off Cape Adare [*Gordon et al.*, 2009].

The outer shelf and upper slope of the NW Ross Sea is dominated by diurnal, barotropic tidal currents having a strong fortnightly cycle. These currents are strongest in coastal areas and over the outer shelf, shelf break and upper slope directly off Drygalski Trough (Figure 1). (A map of maximum tidal currents for the larger NW Ross Sea domain is shown in *Padman et al.* [2009].) Maximum tidal currents up to ~1 m s^{-1} significantly exceeded mean dense outflow current speeds of ~0.6 m s^{-1}. The strongest tidal currents coincide spatially with the steep upper slope (~600-1200 m) over which outflow speed and thickness were greatest.

While this project has contributed to the regional description, its primary effort has been to assess two aspects of the outflow. First is the level of diapycnal mixing associated with the flow, and the impact on this mixing of extremely strong local tidal currents. Second is the impact on the flow of an underlying, continuous field of seafloor corrugations.

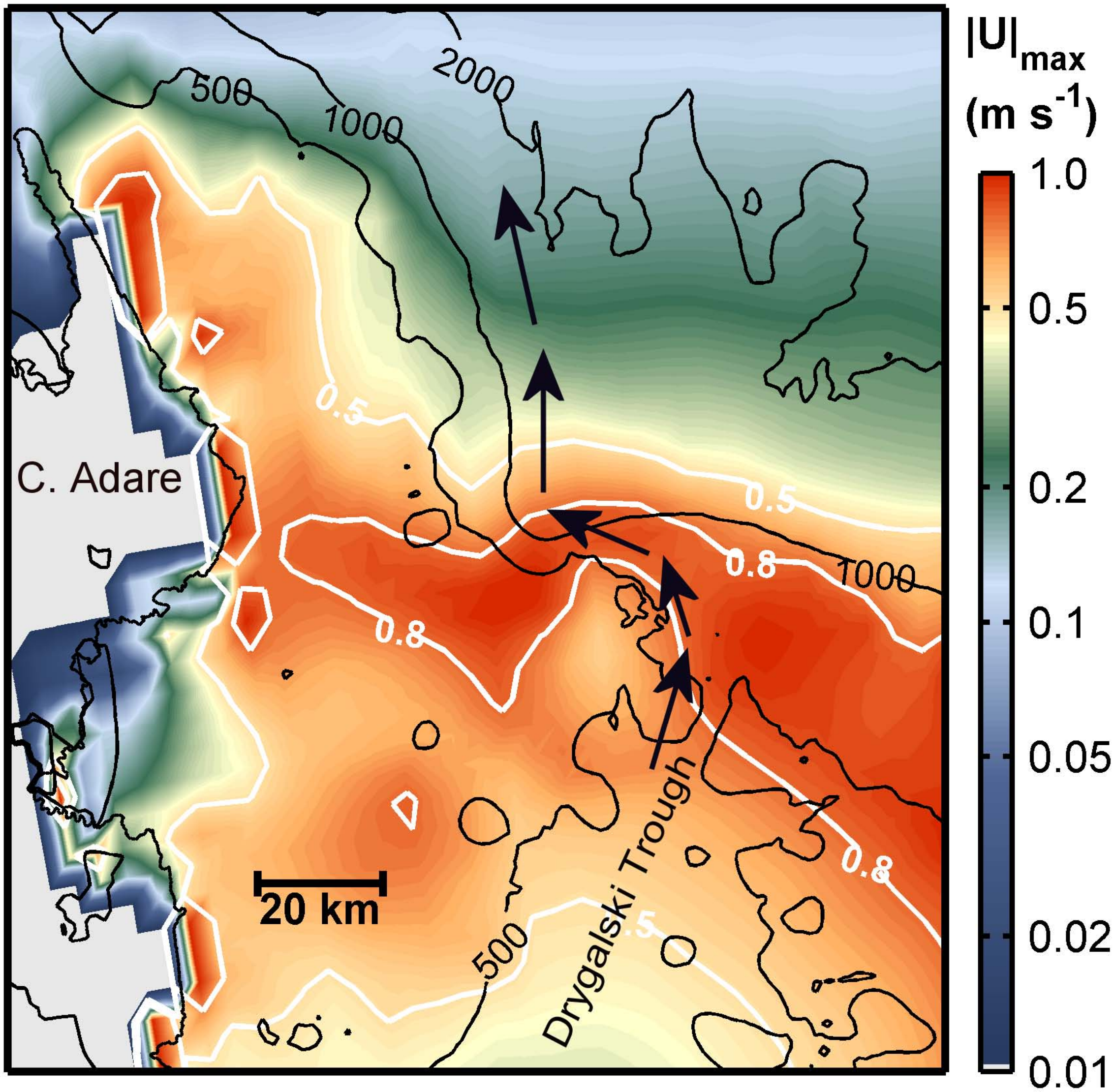

Figure 1. The NW Ross Sea dense outflow traverses a region of very strong tidal currents which impact the outflow. Maximum (spring portion of the fortnightly cycle) tidal current speeds $|U|_{max}$ from barotropic tide inverse model [Erofeeva et al., 2005] are shown from Muench et al. [2009a]. Color scale is logarithmic. White contours show speeds of 0.5 and 0.8 m s^{-1}. Black contours are isobaths. Black arrows show the approximate pathway of the dense outflow.

Mixing and Tidal Impacts

In assessing the tidal contribution to mixing, hydrographic and LADCP current data were used to compute interfacial Froude numbers *Fr*, a measure of the dynamic stability of the flow. Field data for these computations were obtained in summer 2003 during a period of spring tides, and *Fr* was computed according to *Legg et al.* [2008]. Froude numbers exceeded 1 at sites sampled from just off the shelf break to the central slope, with maximum values greater than 1.8 on the upper slope. These values are consistent with interfacial instability and vigorous mixing over the upper and central slope. Vertical diffusivity was then estimated through the transition layer overlying the dense outflow on the same portion of the slope in two ways. First, Thorpe analyses were applied to the hydrographic data using methods discussed by *Thorpe* [1977], *Osborn* [1980] and *Galbraith and Kelley* [1996]. Second, methods discussed by *Osborn and Cox* [1972], *Gregg* [1999] and *Dillon and Caldwell* [1980] were applied to scalar microstructure data obtained from a CTD-mounted microstructure profiler (CMiPS). Both methods yielded diffusivities, averaged over groups of several stations taken within small subareas of the slope, of $K_z > 10^{-3}$ m^2 s^{-1}. The largest group average, ~5 x 10^{-2} m^2 s^{-1}, was found on the upper slope where *Fr* number was largest. Entrainment rates computed from these data, following *Baringer and Price* [1997], agreed within a factor of 2 with that obtained by *Gordon et al.* [2009] using downstream evolution of hydrographic properties. These results are consistent with a prominent role of interfacial stress, associated with diapycnal mixing and associated entrainment, in the momentum balance and downstream evolution of hydrographic characteristics within the flow.

The scalar microstructure data could not be used to compute K_z in the well mixed benthic layer. A 26-hour time series of shear microstructure data was obtained, however, in winter 2004 near the Drygalski Trough sill during the neap portion of the fortnightly tidal cycle. Diffusivities K_z ~ 10^{-3}-10^{-2} m^2 s^{-1} were computed from the shear data following primarily Osborn [1980] and Gregg [1987]. A mean current speed of ~0.2 m s^{-1} was dominated by the diurnal tides. Assuming this current speed and the above value for K_z yielded an Ekman layer depth similar to the observed benthic layer thickness. This agreement is consistent with a tidal impact on benthic layer thickness at the sampled site, however, data were insufficient to extrapolate the tidal dependency farther downslope or from the neap to the spring tidal portion of the fortnightly cycle. A three-dimensional, primitive equation ocean tide model, discussed in detail in *Padman et al.* [2009] was used to provide further context for tidal impact on mixing of the outflow. Model results extended from the locale of the shear microstructure time series down the slope, allowing extrapolation to regions not covered by the field data. Modeled benthic layer depths at the location where shear microstructure data were acquired were consistent with observed conditions. Likewise, modeled mean values of K_z, and the spread of values through a tidal cycle, were similar to those computed from the microstructure data. Sensitivity studies were done using simulations for both neap and spring tide conditions, and model results were compared with both the observed winter 2004 (neap) and summer 2003 (spring) stratification both at the sill and at ~ 900 m depth on the upper slope (Figure 2). Spring tide conditions yield, as opposed to neap conditions, greater scatter in the density profiles, particularly in the benthic layers, at both sites. The greatest impact, however, was on diapycnal diffusivity K_z, which was greatly enhanced through most of the water column during spring as compared to neap tides. These results were consistent with *Whitworth and Orsi* [2006], who noted extension of energetic mixing throughout most of the water column during spring tides.

Model and field data are concluded to be consistent with an increase of the vertical eddy viscosity A_z in the benthic layer by a factor of ~2 during spring as compared to neap tides. Further, spring tide currents enhance downslope Ekman transport and Ekman mixing depth by 60-70% relative to the neap case. Mooring data [Whitworth and Orsi, 2006] and output from a three-dimensional, tide forced ocean model [Padman et al., 2009] suggest, finally, that benthic stress during spring tides is sufficiently vigorous to augment shear-driven entrainment at the outflow's upper interface.

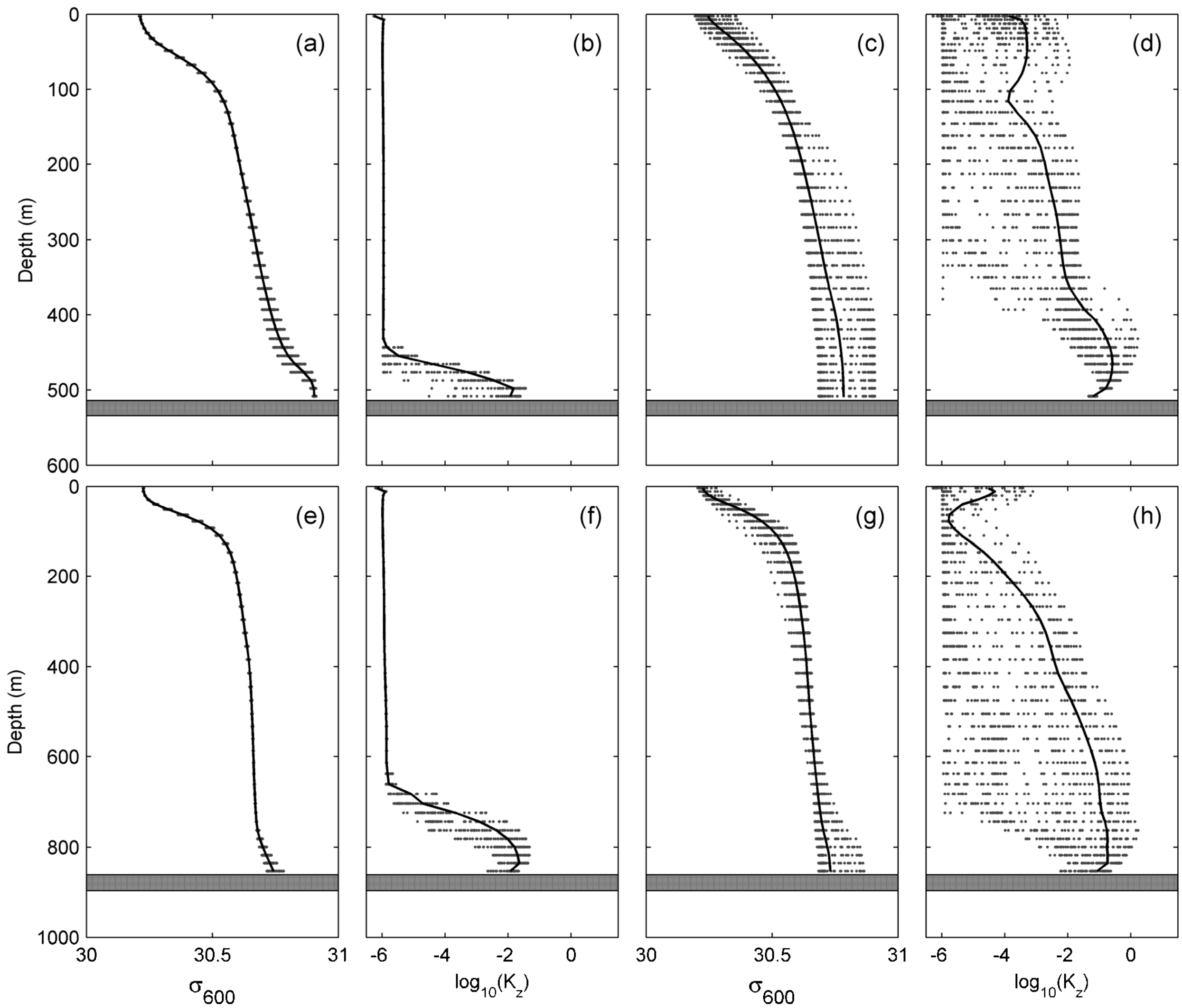

Figure 2. Results from a tidally-forced model predict tidal impacts on vertical stratification on the upper slope [Muench et al., 2009a]. Plots show modeled potential density (σ_{600}) and vertical diffusivity K_z near the Drygalski Trough sill (upper panels) and near 900 m depth on the upper slope (lower panels). Dots in each plot show hourly instantaneous values at the 41 model levels, while black curves show mean profile over two K_1 tidal cycles (2 days). Panels (a), (b), (e) and (f) show neap tide forcing, while panels (c), (d), (g) and (h) show spring forcing. Top of the grey box at the bottom of each panel shows model water depth.

Impact of Seabed Corrugations

Shipboard field activities in the NW Ross Sea included detailed bottom mapping using a sidescan sonar. This mapping revealed the slope over which the dense outflow passed to be cut with a continuous field of downslope-trending corrugations. These features have vertical trough to crest amplitudes of 10-20 m, and alongslope wavelengths of 1-2 km. Previous work by *Wåhlin* [2004] has shown that such corrugations can channel dense bottom flows downslope, enhancing the overall downslope transport of the flow. An analytical model was applied to the NW Ross Sea case, using outflow thickness, bottom slope and corrugation dimensions appropriate to the region [*Muench et al.*, 2009b]. Results for a single trough reveal that the wavelengths were optimal for enhancing downslope transport, but that the vertical amplitudes were too small to enhance downslope flow by more than ~5% of the mean downslope component of the outflow.

Two numerical simulations were then run, using parameterizations appropriate to the region, in order to check for compatibility with the analytical results and to compare the outflow response to a field of corrugations to that for a single trough [*Muench et al.*, 2009b]. The two simulations had distinct computational characteristics. One was the nek5000 model used previously by *Özgökmen and Fischer* [2008] in dense outflow simulations, and the other was the Generalized Ocean Layer Dynamics (GOLD) model, an isopycnal coordinate, hydrostatic model. Both models had horizontal and vertical resolution more than adequate to define the processes of interest. Simulations from both models yielded regional geostrophic adjustment until reaching final states with eddies along the upper slope and a slow, downslope near-bottom Ekman flux. Sensitivity studies run with the nek5000 model using both a smooth bottom and varying corrugation amplitude and wavelength yielded a maximum corrugation-driven downslope transport for wavelengths of ~1 km, within the "realistic" range for the region. The amplitudes for these runs were, however, constrained by model limitations to be too large by a factor of ~10. A series of simulations was then undertaken using the GOLD model using a fixed "realistic" wavelength of 2 km and variable amplitudes, in order to test for dependence of the downslope transport on amplitudes down into a realistic range. Results of this simulation (Figure 3) reasonably reproduce the mean outflow pathway and reveal that the impact of corrugations increases with increasing amplitude for the given wavelength. The simulation using a realistic amplitude shows little change from the smooth bottom case, though flow down individual corrugations is apparent. That using an amplitude that is unrealistically large for the Ross Sea clearly shows the impact of the corrugations. The enhanced downward flow causes the outflow to reach the bottom of the slope sooner and at a different location than for the smooth bottom case. While we have not quantitatively assessed the role of corrugations in diapycnal mixing, it might be assumed that less mixing would occur during the more rapid, corrugation assisted descent than for the smooth bottom case. In any case, presence of corrugations impacts the point at which an outflow reaches the abyss, the final water mass characteristics, and the depth, through impacts of the mixing on density, at which the flow interleaves into abyssal waters.

IMPACT/APPLICATIONS

Results of this research have greatly increased our quantitative and dynamical understanding of the dense outflow that exits the NW Ross Sea continental shelf. This flow may contribute as much as 25% of the source water for the AABW that underlies much of the world ocean and that is critical for the Southern Ocean branch of the MOC. This understanding is essential to prediction of interactions among climatic and upper ocean changes and the formation rate of AABW. Results dealing with smaller scale processes such as tidal impacts on the dense outflow and interactions between the flow and small-scale bottom topographic features have application to the many other regions in the world ocean where gravity currents are present. Improved dynamical understanding of these relatively small scale processes can contribute to their accurate representation in large scale numerical models that are presently used for long-term prediction. The need for improved understanding of gravity currents is comprehensively argued in *Legg et al.* [2008].

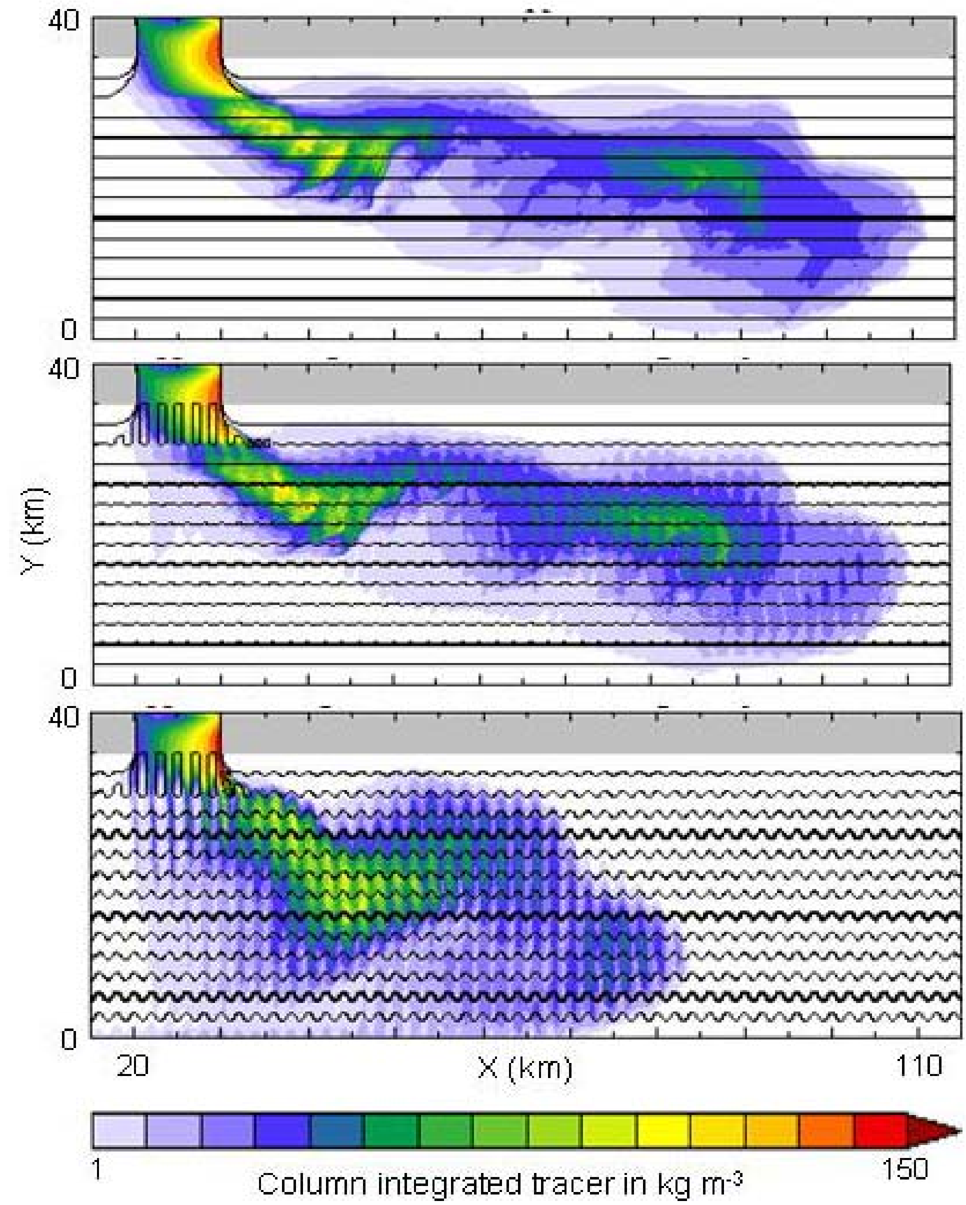

Figure 3. Horizontal distribution of a tracer introduced into a dense outflow at the sill for the NW Ross Sea case, using the GOLD model spun up for 4 days, for: (upper) smooth bottom simulation; (middle) "realistic" simulation ; and, (lower) simulation using unrealistically large corrugation amplitude [from Muench et al., 2009b]. See text for details.

RELATED PROJECTS

Research carried out under this grant is topically related to, and has been carried out in collaboration with researchers in, the following projects:

- AnSlope (Antarctic Slope Project): A study of the impacts of shelf break dynamical processes on the transport of dense water from near-coastal formation region to the deep ocean floor [*Gordon et al.*, 2009].

- GCECPT (Gravity Current Entrainment Climate Process Team): A dedicated research group focused on dense overflow processes and potential interactions with climate [*Legg et al.*, 2008].

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